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ENGR 4940U Capstone Systems Design for ECSE II
System Design of Bi-Directional EV Charger with Grid Optimization

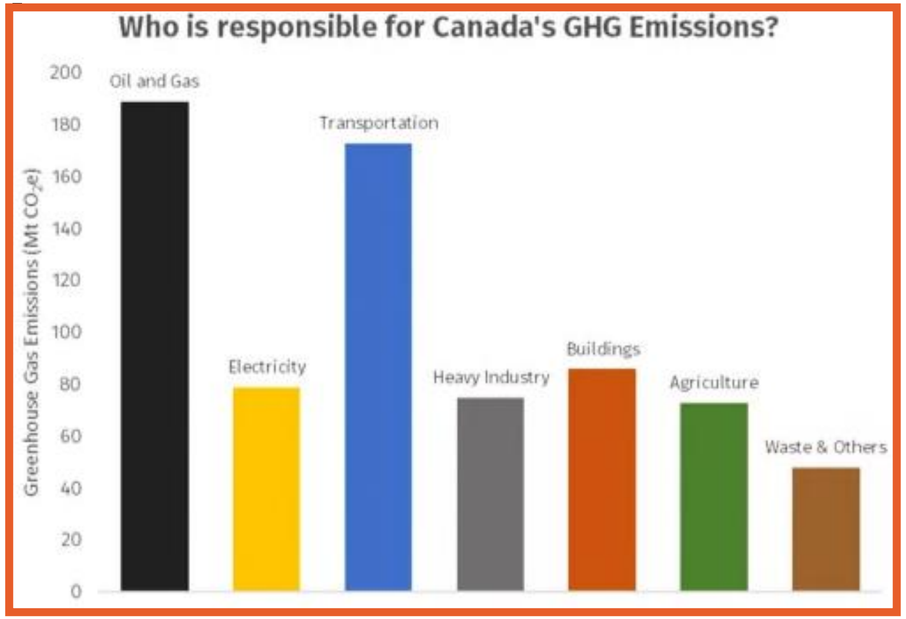
Capstone Coordinator: Dr. Qusay Mahmoud *Faculty Advisor:* Dr. Mohamed Youssef

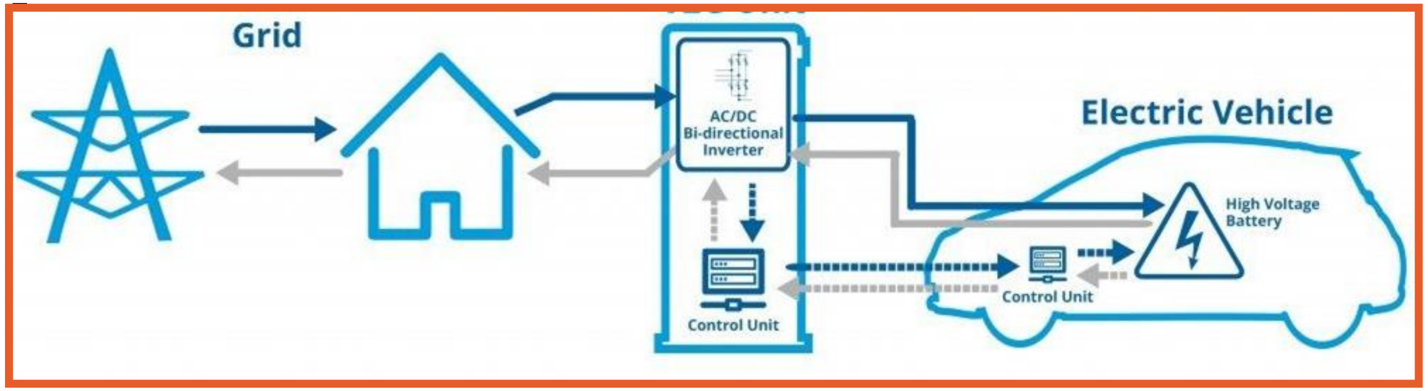
Overcoming Initial Challenges

Challenges	How we overcame it
Little to no background knowledge in Power Electronics	- Extensive research on the topics, components, systems associated with our design
Little background knowledge on Smart Grid	- Extensive research on Smart Grid concepts learned in lecture
Being introduced to a new type of software (PSIM) used for the system design and simulation	- Read PSIM software manual - Communicated with PSIM tech advisors - Watch various tutorial videos
Limited availability of new components on the market (i.e. bi-directional grid inverter)	- Creative integration of microcontroller, relays, and rectifier/inverter

Overview & Problem Identification

What are you trying to do?





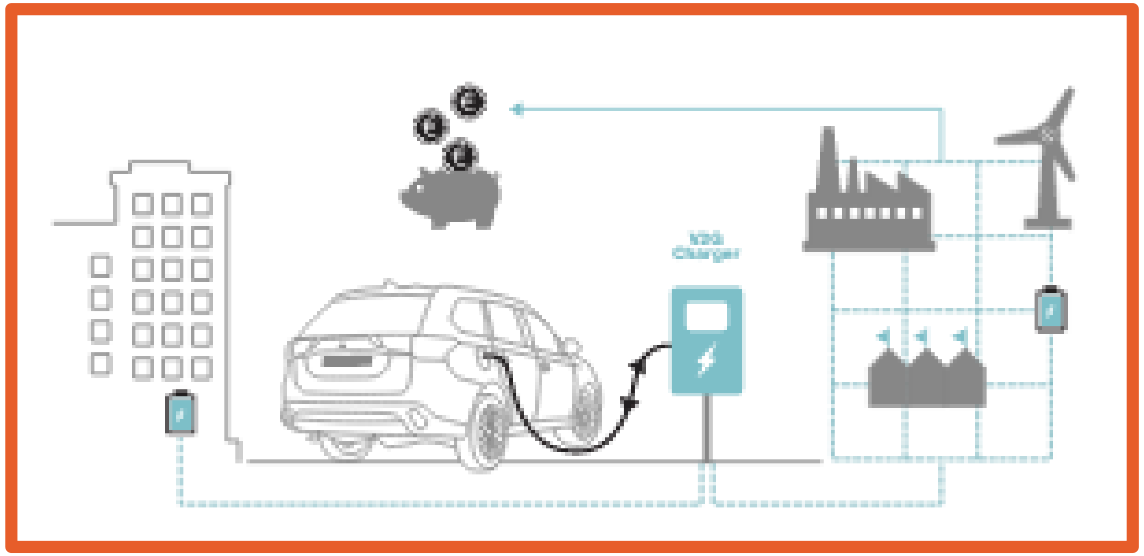
How is it done today, and what are the limits of current practice?

- <u>AC Level 1:</u> 120 V, 1.4 kW @ 12 A
  120 V, 1.9 kW @ 16 A
- *PHEV:* ~7hrs for 0% to full
- *BEV:* ~17hrs for 20% to full
- <u>AC Level 2:</u> 240 V, up to 19.2 kW @ 80 A
  Depending on power rating of on-board charger:
- *PHEV:* 22min-3hrs for 0% to full
- *BEV:* 1.2hrs-7hrs for 20% to full

What's new in your approach and why do you think it will be successful?

New Approach

- DC Charging
- Focus is Vehicle to Grid (V2G)
- Reduction of demand on grid during peak hours
- Coupling the supply to grid from PV with charging of EV's in one complete package



Success Potential

- Battery protection
- Fast charging to meet consumer needs
- Strain reduction on grid during peak hours

What evaluation have you done to demonstrate your proof of concept is better than existing solutions?

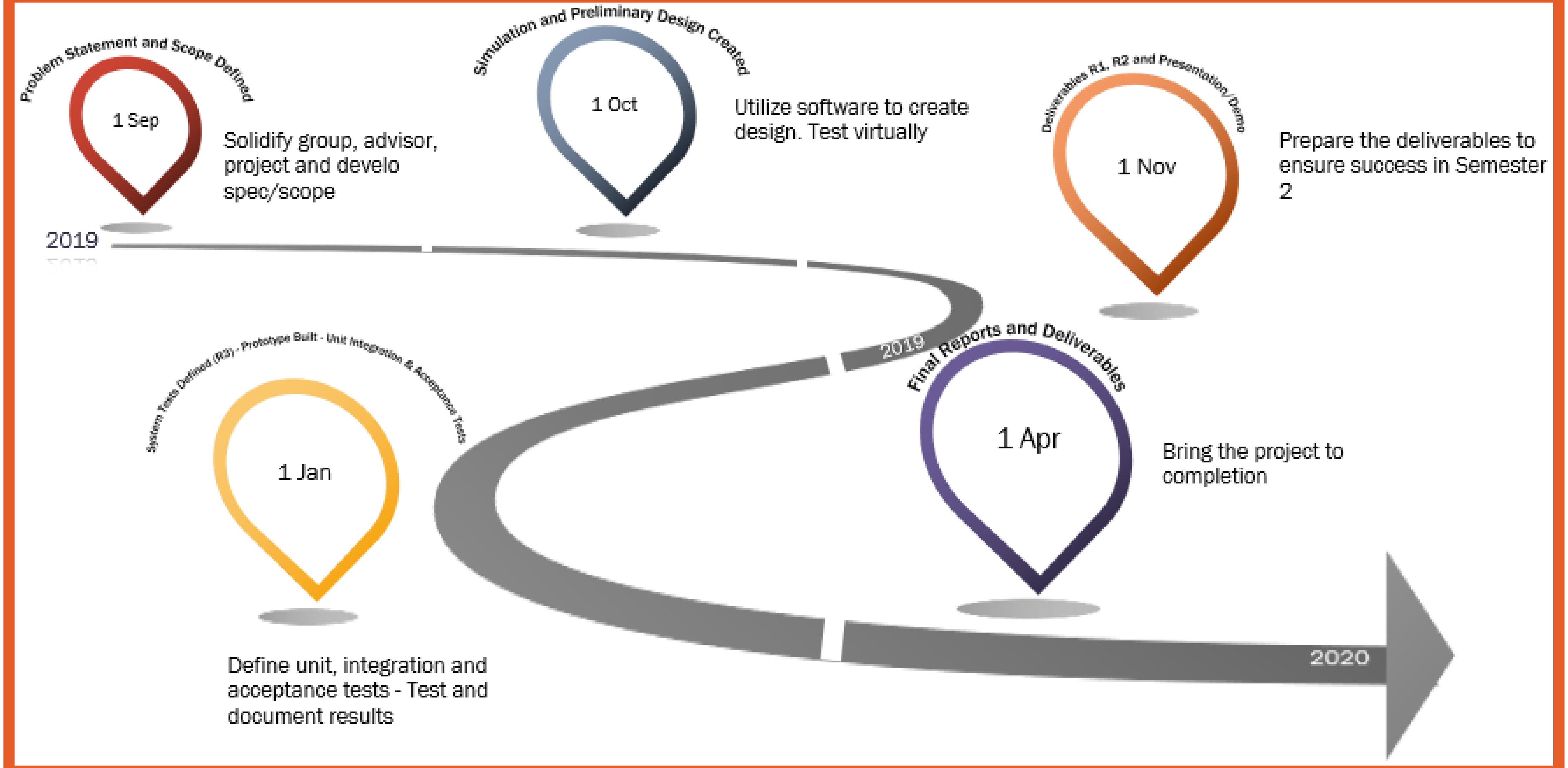
- Physical recording of DC charging is inherently faster than the rate of charge for AC charging
- Charging time of our system is roughly 20 minutes (from low level voltage to nominal voltage of the battery)
- Ability to switch to grid supply when battery is above nominal threshold to stabilize the grid during peak hours
- Vehicle to Grid (V2G) capability at user's discretion; able to use batteries charge to feed the grid when PV is unavailable

Who cares? If successful, what difference will it make?

There are 3 overarching differences that a successful bi-directional charging system can accomplish:

1. PV Optimization
   - Making use of renewable energy resources - to grid or to EV
2. Providing a solution to infrastructure needs with growing renewable energy sources and electric vehicles
3. Grid Optimization
   - Vehicles can supply electric power back to the grid
     - Optimization – Managing of peak demand
   - Users have the ability to make money with their vehicles
     - Supplying back to the grid during on-peak, charging/drawing when demand is lower

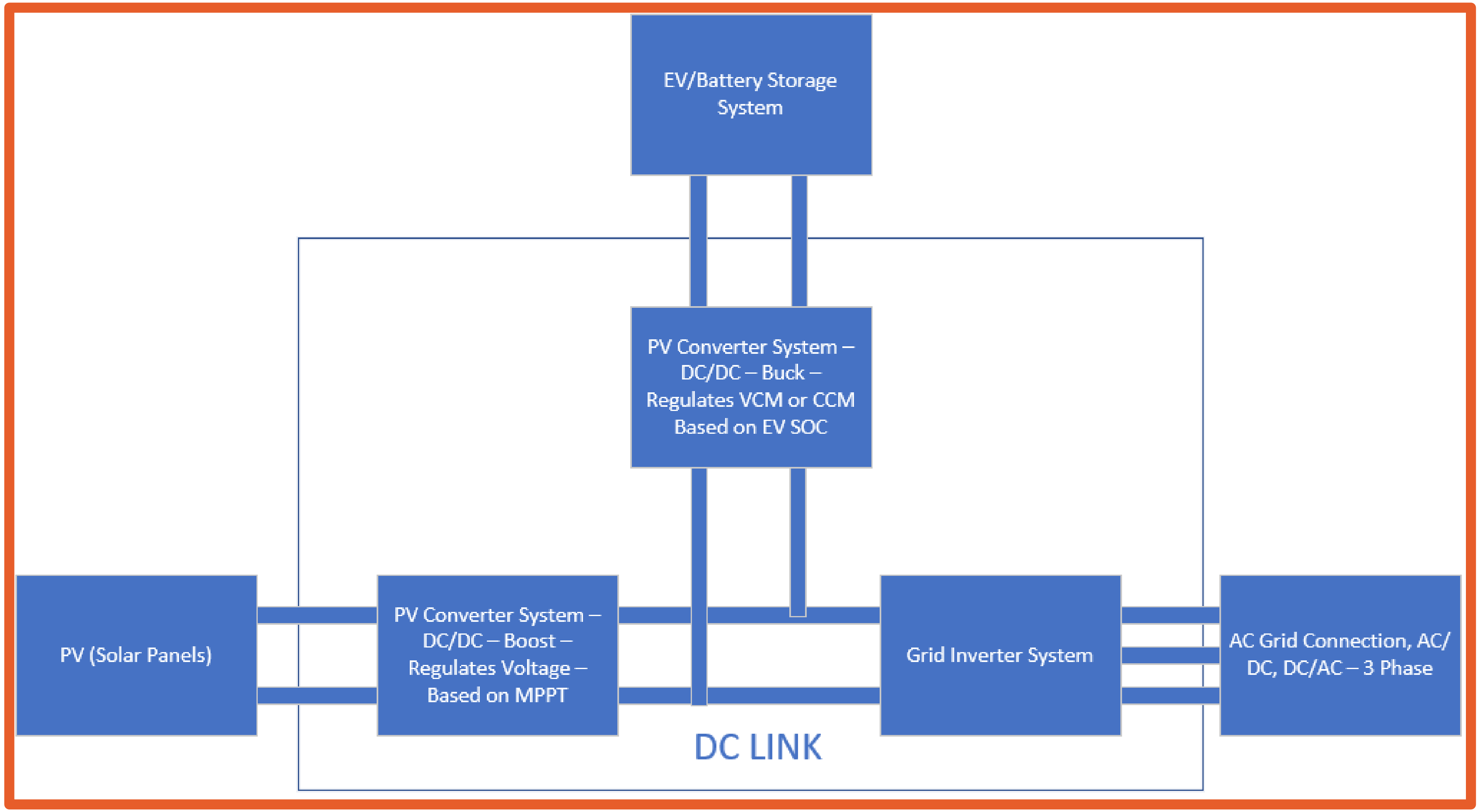
How Long Did it Take? A Timeline:



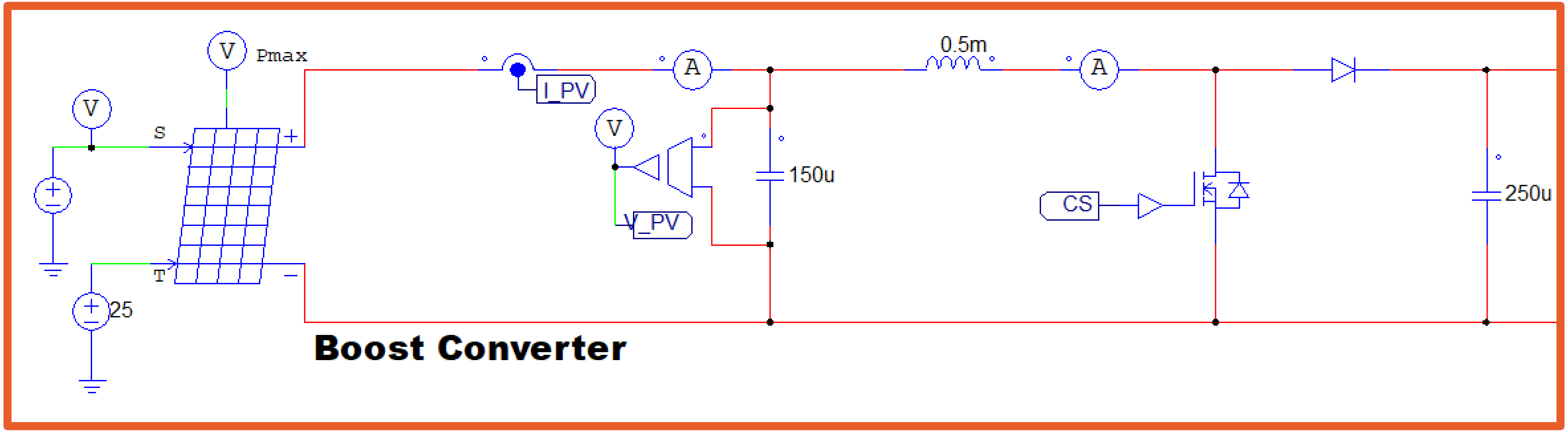
What are the midterm and final ’exams’ to check for success?

- Unit Testing
  - Testing of individual components
- Integration Testing
  - Testing of clusters of components
- Acceptance Testing
  - Testing of system scenarios to ensure marketing and engineering requirements fulfilled

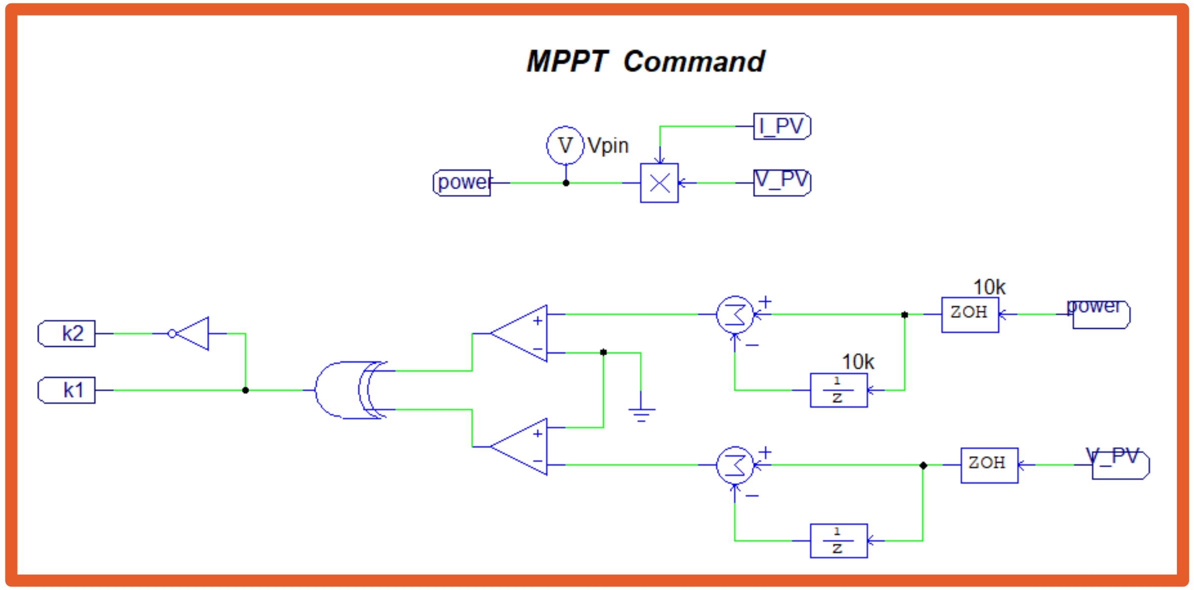
High Level System Block Diagram

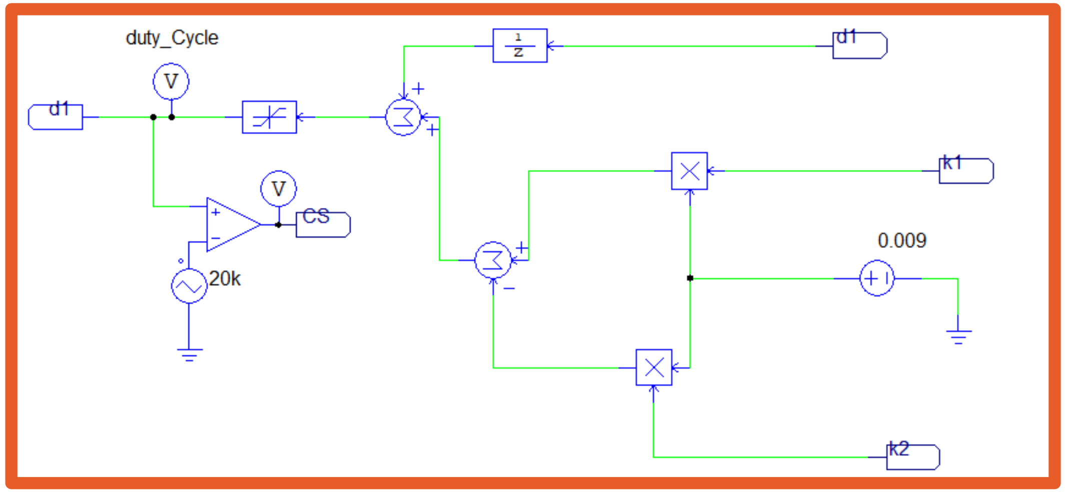


DC/DC Boost Converter



MPPT Command for DC/DC Boost Converter Switch





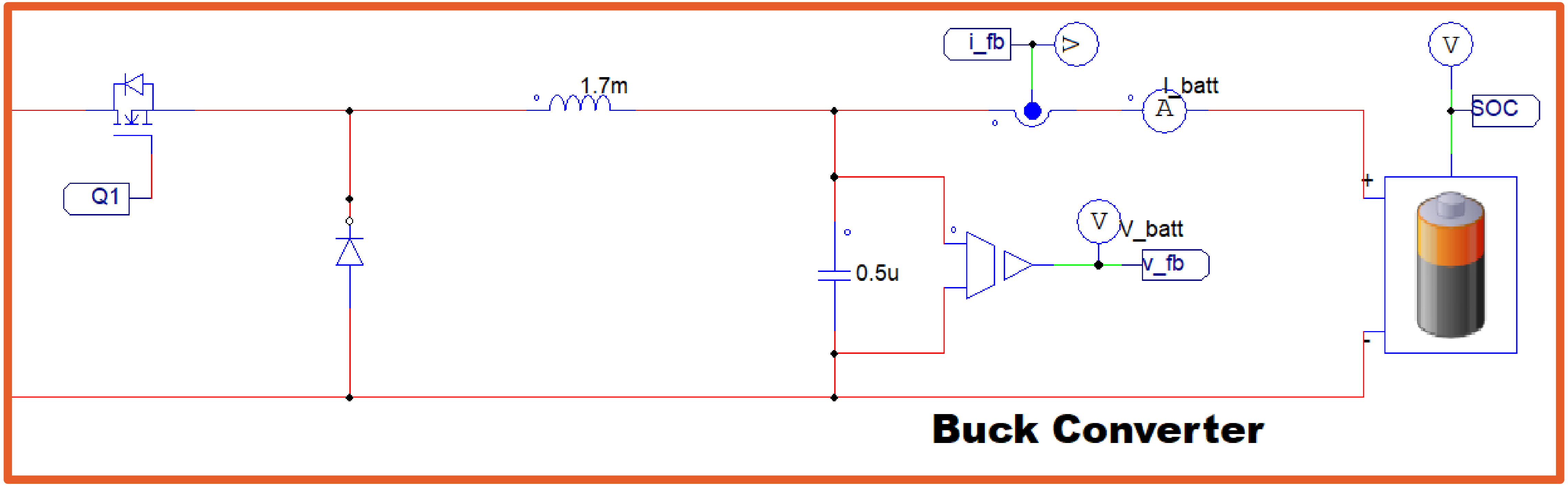
Prototype Implementation of Boost Converter

- As part of our initial design, we needed to incorporate a boost converter that encompassed MPPT control in order to extract the maximum available power from the PV
- This component was selected due to the following ratings:
  - Input Voltage: 12V-60V
  - Output Voltage: 15V-90V
  - Output Current: 0A-15A

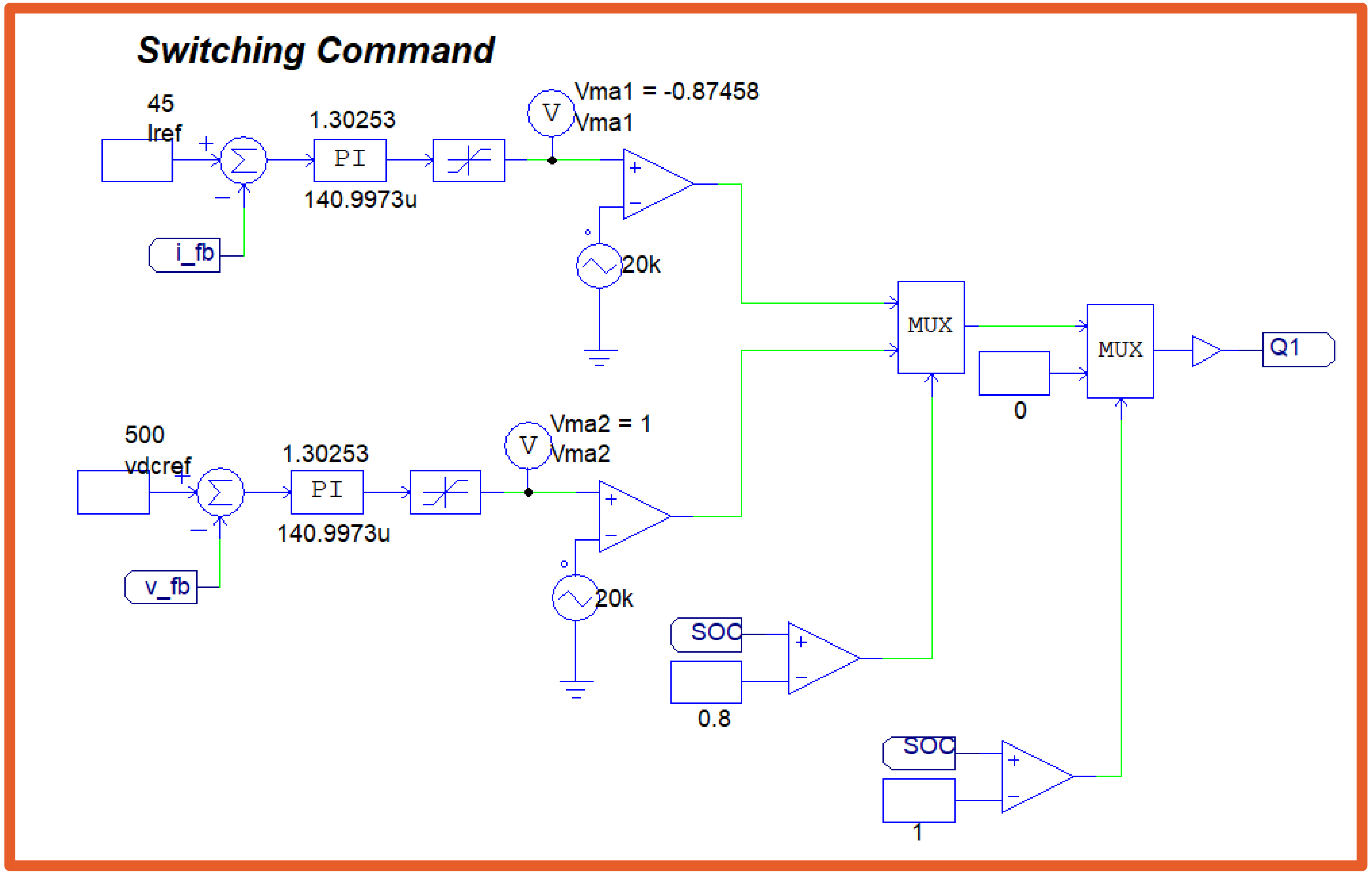
- Some additional features that this component provides are overload protection, overtemperature protection, and overcurrent protection

- These component specifications met our system design requirements of:
  - Input Voltage: 12 VDC
  - Output Voltage: 15 VDC
  - Output Current: 1.5 A

DC/DC Buck Converter



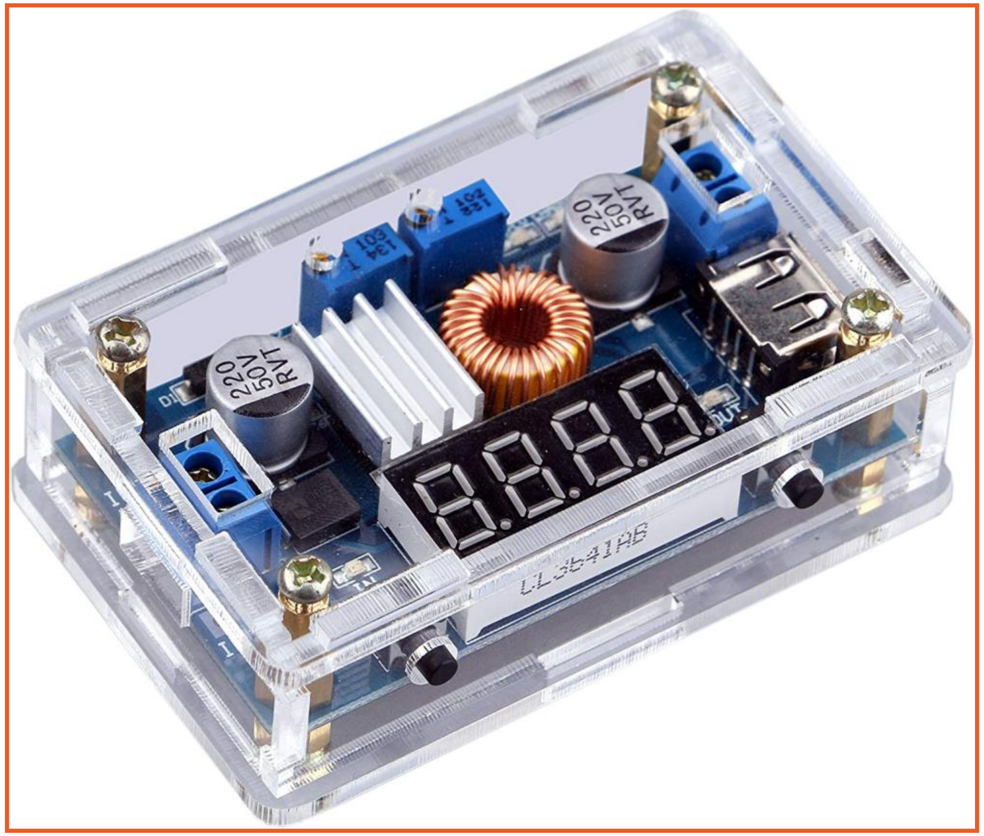
Switching Command for DC/DC Buck Converter



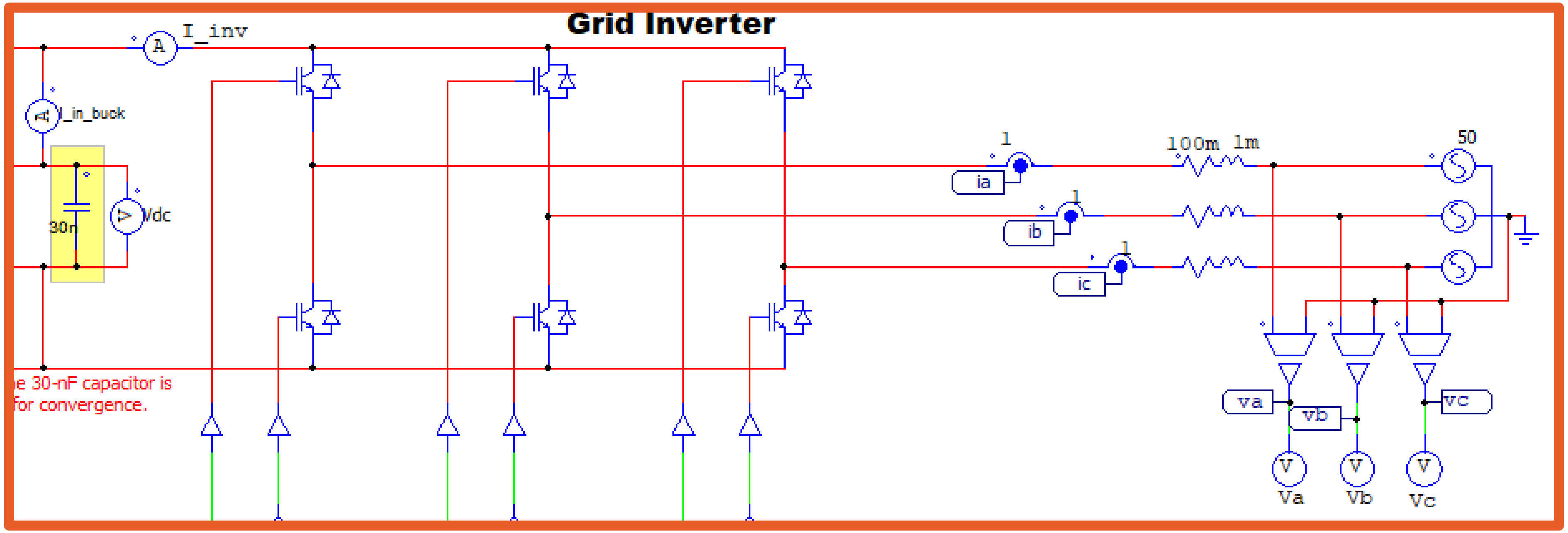
Prototype Implementation of Buck Converter

- A component was selected to accept the following ratings:
  - Input Voltage: 7-36 VDC
  - Output Voltage: 1.25-32 VDC
  - Output Current: Up to 5 A

- These component specifications met our system design requirements of:
  - Input Voltage: 15 VDC
  - Output Voltage: 12 VDC
  - Output Current: 1.5 A



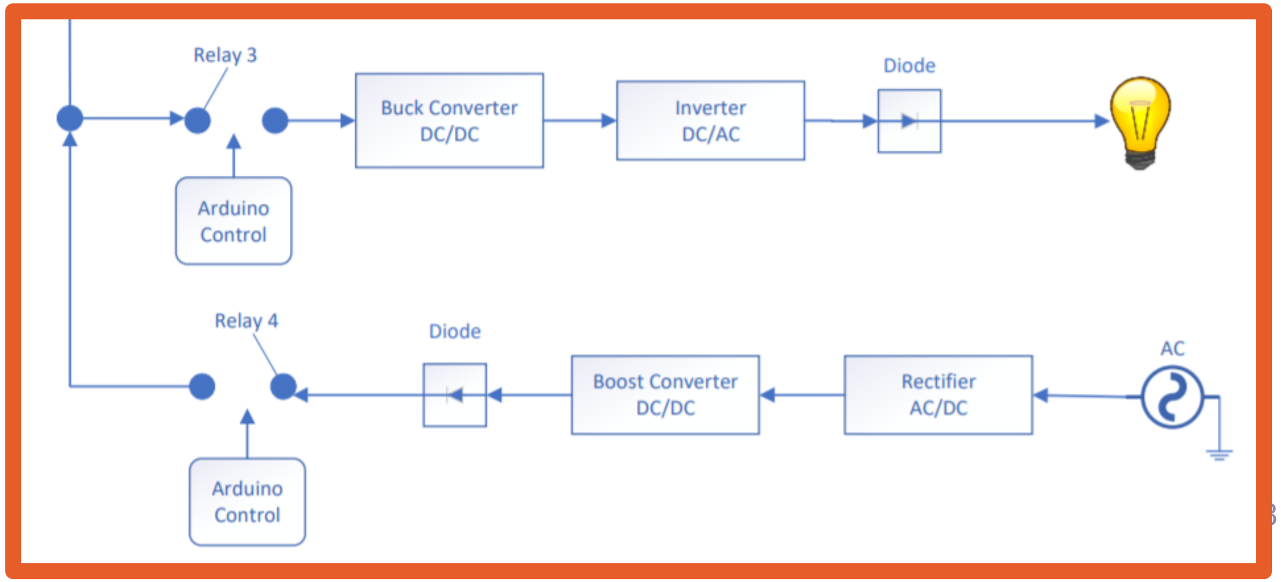
Grid Inverter



- Grid-side infrastructure has the ability to take 3-phase grid power and rectify it to DC power
- Power can flow in the other direction, and using the switches, can be inverted to send back to the grid
- PWM to be used in order to switch IGBT's on and off periodically in order to invert or rectify power accordingly
- IGBT's used over diodes to add controllability (makes use of PI control circuit

Prototype Implementation of Grid Inverter

- At first, our design incorporated a single component to act as our bidirectional inverter
- After spending a lot of time searching the market, we were unable to find a suitable component to act as our bidirectional inverter
- We had contacted different companies via email as well as having sit down meetings with a few local engineering and energy solution companies that were not able to provide us with a suitable solution for this portion of the project
- At this point, we had decided to split up that single component into two components that would act as a bidirectional inverter
- We chose to have two branches of power flow to and from the grid; to the grid we used a DC/AC inverter (12V DC to 120V AC) and from the grid we used an AC/DC rectifier (120V AC to 12V DC)



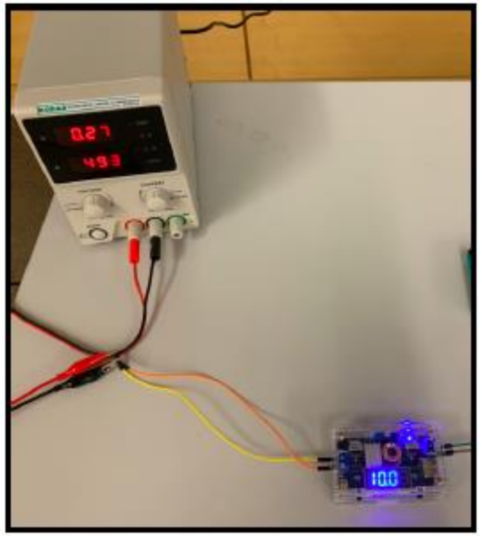
How much will it cost?

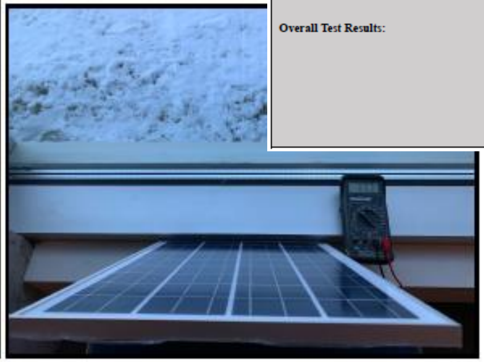
Bill of Materials				
Part No.	*Part Name*	*Qty.*	*Unit Cost ($)*	*Total Cost ($)*
1	DROK Boost Voltage Converter w/ MPPT Controller	1	56.99	56.99
2	Drok Micro Led DC/DC Digital Boost Voltage Converter	2	12.56	25.12
3	Yeeco DC/DC Buck Converter w/ Constant Voltage & Current Regulator	2	18.99	37.98
4	ARDUINO MEGA2560	1	49.95	49.95
5	Power Inverter	1	36.78	36.78
6	ECO-WORTHY 12V 25W Solar Power Kit	1	58.99	58.99
7	SainSmart 4-Channel Relay Module	1	11.99	11.99
8	100uF Capacitors	1	32.26	32.26
9	12V Max 2Ah Lithium Power Tool Battery	1	41.22	41.22
10	Voltage Sensor for ARDUINO	2	25.38	50.76
11	Diode 6A 400V	4	1.50	6.00
12	Rectifier AC-DC	1	50.75	50.75
***TOTAL COST*: $458.79**				

Testing Methodology - Unit Tests

PURPOSE: Unit tests were used to assess the functionality of individual components. Unit tests were completed prior to integration tests.

Test Writer: Daniel Luciano, Updated by: Payton Sainsbury on 20-Feb-2020						
Test Case Name:	DC-DC Buck Converter Functionality Test		Test ID #:		004	
Description:	Ensure that when the DC voltage passed from the DC Link (~15 V) is applied to the Buck converter it is able to step down the voltage to a constant of DC voltage of 12 V.		Type:		[ ] White Box [X] Black Box	
Tester Information: N/A						
Name of Tester:	Daniel Luciano & Myson Martin		Date:		20-Feb-2020	
Software Version:	N/A		Time:		1:30pm	
Setup:	DC-DC Buck converter to be tested, DC power supply to generate input voltage signal of 15V at the input end of converter. The voltage will be passed through the converter, the output voltage will be read off of the converter's LCD display to ensure the voltage has been stepped down to 12 V.					
Step	Action	Expected Result	P	F	N/A	Comments
1	Configure DC power supply to provide 15 V. Connect voltage source to input terminals of converter.	N/A - Setup.			X	N/A
2	Configure the voltage potentiometer on the Buck converter to output 12 VDC.	Read an output voltage of 12 V from the converter's LCD display screen.	X			LCD screen on Buck converter displayed an input voltage of 14.98 V and an output voltage of 11.96 V.
Overall Test Results:			X			N/A





Test Writer: Payton Sainsbury, Updated by: Payton Sainsbury on 20-Feb-2020						
Test Case Name:		Solar Panel (PV) Functionality Test	Test ID #:		001	
Description:		Ensure that PV outputs some fluctuating voltage at output depending on light source availability.	Type:		[ ] White Box [X] Black Box	
Tester Information: N/A						
Name of Tester:		Jesse Otto, Daniel Luciano & Payton Sainsbury	Date:		20-Feb-2020	
Software Version:		N/A	Time:		11:00am	
Setup:		PV required for testing, breadboard to connect PV to load, 1 kΩ load resistor connected to breadboard, varying light source (indoor lighting and natural lighting), multimeter to take measurements across resistor				
Step	Action	Expected Result	P	F	N/A	Comments
1	Connect the 1 kΩ load resistor to the breadboard. Connect the output cables from	N/A - Setup.			X	N/A
	the solar panel to the breadboard on either side of the load resistor to supply power.					
2	Apply the light source to the PV and use the multimeter to measure voltage across and current through the resistor.	Measure at least ~12 V across the resistor at output to ensure the input to the DC-DC Boost Converter will be within an acceptable range. Measure current through the resistor and use these values to calculate wattage, expect to get out ~4.2 W.	X			Open circuit output voltage was measured at 17.70 V. When the 1 kΩ resistor was attached in series via breadboard to act as a load, the output voltage was measured at 14.75 V
Overall Test Results:			X			PV is supplying appropriate voltage/current levels which are within the acceptable input range for the DC-DC boost converter.

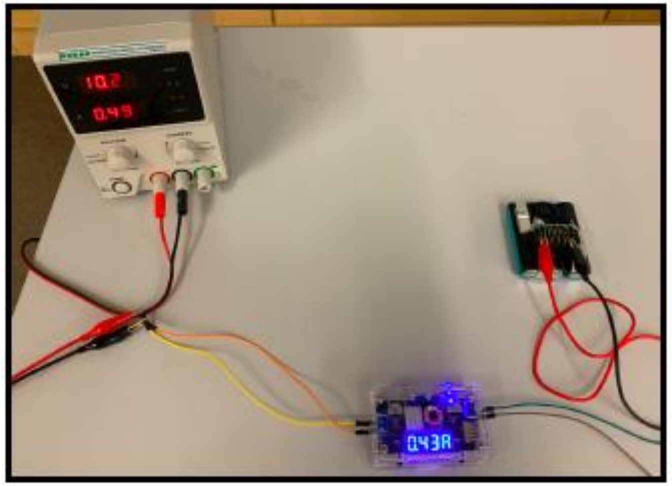
Figures: Sample Unit Tests

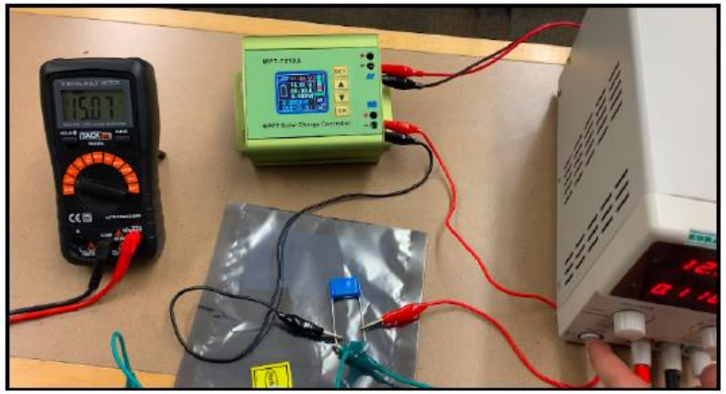
Testing Methodology - Integration Tests

PURPOSE: Integration tests were used to assess the functionality of clusters of components. Components were tested individually during the unit testing stage. Integration tests confirmed the assembly.

Test Writer: Payton Sainsbury, Updated by: Payton Sainsbury on 28-Feb-2020			
Test Case Name:	Battery and DC-DC Buck Converter Integration Test	Test ID #:	007
Description:	Ensure that the battery is able to be safely charged by the buck converter.	Type:	[ ] White Box [X] Black Box
Tester Information: N/A			
Name of Tester:	Daniel Luciano, Myson Martin	Date:	28-Feb-2020
Software Version:	N/A	Time:	1:00pm
Setup:	DC-DC buck converter, DC power supply to generate input voltage signal of 15V at the input end of the buck converter. The DC voltage will be stepped down through the converter, and the battery will be connected to the converter's output. A multimeter will be used to ensure the battery is charging.		

Step	Action	Expected Result	P	F	N/A	Comments
1	Configure DC power supply to provide 15 V to the buck converter input. Connect voltage source to input terminals of converter. Connect 12 V battery across the output of the converter. Let the battery charge. Use the multimeter to measure the state of charge of the battery.	State of charge of the battery increases.	X			Upon connecting the DC power supply to the buck converter and converter to the battery, the buck converter lit up and began to display the input voltage and the output voltage (15V and 12V respectively). A multimeter was placed across the battery's terminal and it displayed a rising voltage confirming that the battery's voltage level was increasing (ie. charging)
Overall Test Results:			X			Issues summarized in Issues & Defects section of this report.





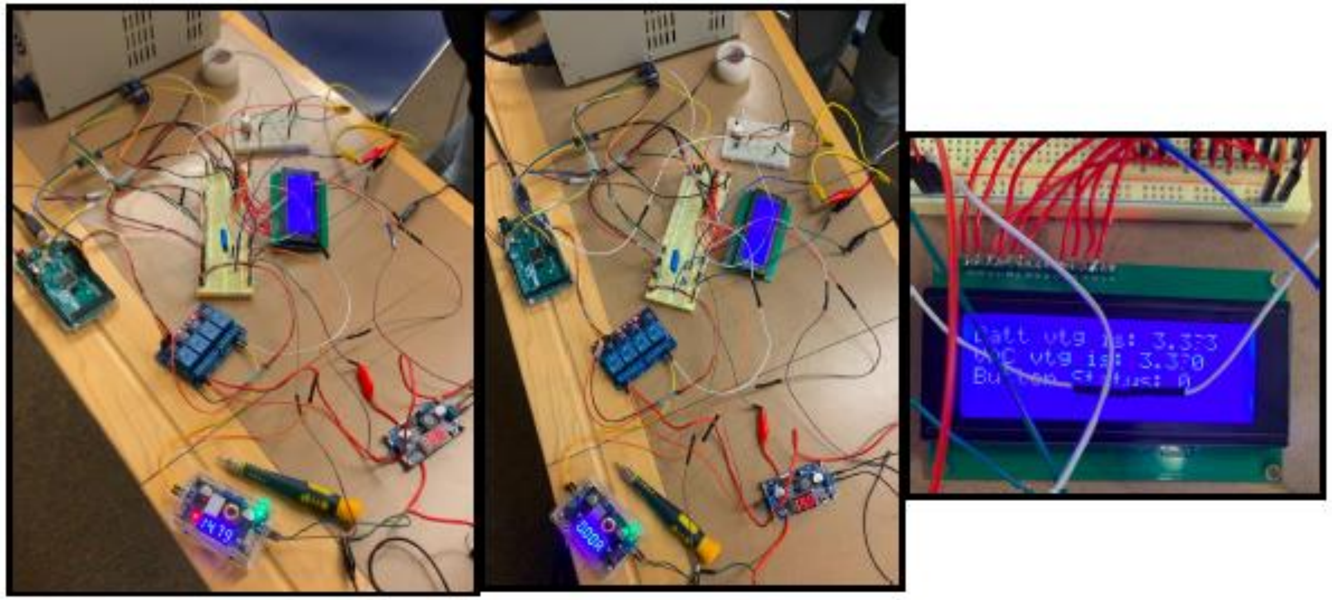
Test Writer: Payton Sainsbury, Updated by: Payton Sainsbury on 4-Mar-2020			
Test Case Name:	Boost Converter and DC Link Integration Test	Test ID #:	008
Description:	Ensure that the DC link capacitor is able to be charged by the boost converter and store a regulated voltage at ~15 V	Type:	[X] White Box [ ] Black Box
Tester Information: N/A			
Name of Tester:	Daniel Luciano & Payton Sainsbury	Date:	4-Mar-2020
Software Version:	N/A	Time:	4:45pm
Setup:	100 µF capacitor voltage to be tested, boost converter to supply voltage to the capacitor, multimeter to take voltage measurement across capacitor		

Step	Action	Expected Result	P	F	N/A	Comments
1	Configure DC power supply to provide 12 V to the boost converter input. Connect voltage source to input terminals of converter. Connect boost converter output to capacitor terminals. Take multimeter voltage reading across the capacitor.	Capacitor is able to hold a charge and thus measure a regulated DC voltage of 15 V.	X			While the boost converter was connected to the capacitor, a steady voltage of 15 VDC was read across the capacitor terminals. The boost converter was then disconnected and the multimeter showed the voltage across the capacitor dissipating (i.e. the capacitor was discharging).
Overall Test Results:			X			N/A

Testing Methodology - Acceptance Testing

PURPOSE: Acceptance testing was completed after integration testing. Testing of system scenarios to ensure marketing and engineering requirements fulfilled.

Test Writer: Daniel Luciano & Payton Sainsbury						
Test Case Name:		Acceptance Test 1	Test ID #:		156	
Description:		To verify that EV can be charged from either PV or grid when PV is unavailable.	Type:		[ ] White Box [X] Black Box	
Tester Information: N/A						
Name of Tester:		Jesse Otto & Myson Martin	Date:		6-Mar-2020	
Software Version:		N/A	Time:		7:45pm	
Setup:		Refer to Figure 1.1 for complete system block diagram. This setup will be used throughout Acceptance Testing.				
Step	Action	Expected Result	P	F	N/A	Comments
1	Verify EV is charging while PV source is available.	PV to supply 12 VDC to boost converter input. Boost converter to supply 15 VDC to DC Link. Relay 1 to be ON. DC Link to supply 15 VDC to buck converter. Buck converter to supply 12 VDC to battery. Relays 2, 3, and 4 to be OFF.	X			Appropriate input/output voltage measurements read off of each of the converter's LCD screens. Battery voltage shown increasing on system level LCD screen.
2	Verify that when PV source becomes unavailable, system switches to draw power from grid in order to charge battery.	Grid to provide 120 VAC single phase to rectifier. Rectifier to output 12 VDC to input of boost converter. Boost converter to supply 15 VDC at output to charge DC Link. DC Link to supply 15 VDC to buck converter. Buck converter to supply 12 VDC to battery. Relays 1 & 4 to be ON and Relays 2 & 3 to be OFF.	X			Appropriate input/output voltage measurements read off of each of the converter's LCD screens. Battery voltage shown increasing on system level LCD screen.
Overall Test Results:			X			Our system is behaving as expected in both scenarios where EV is required to be charged.



What requirements have been implemented?

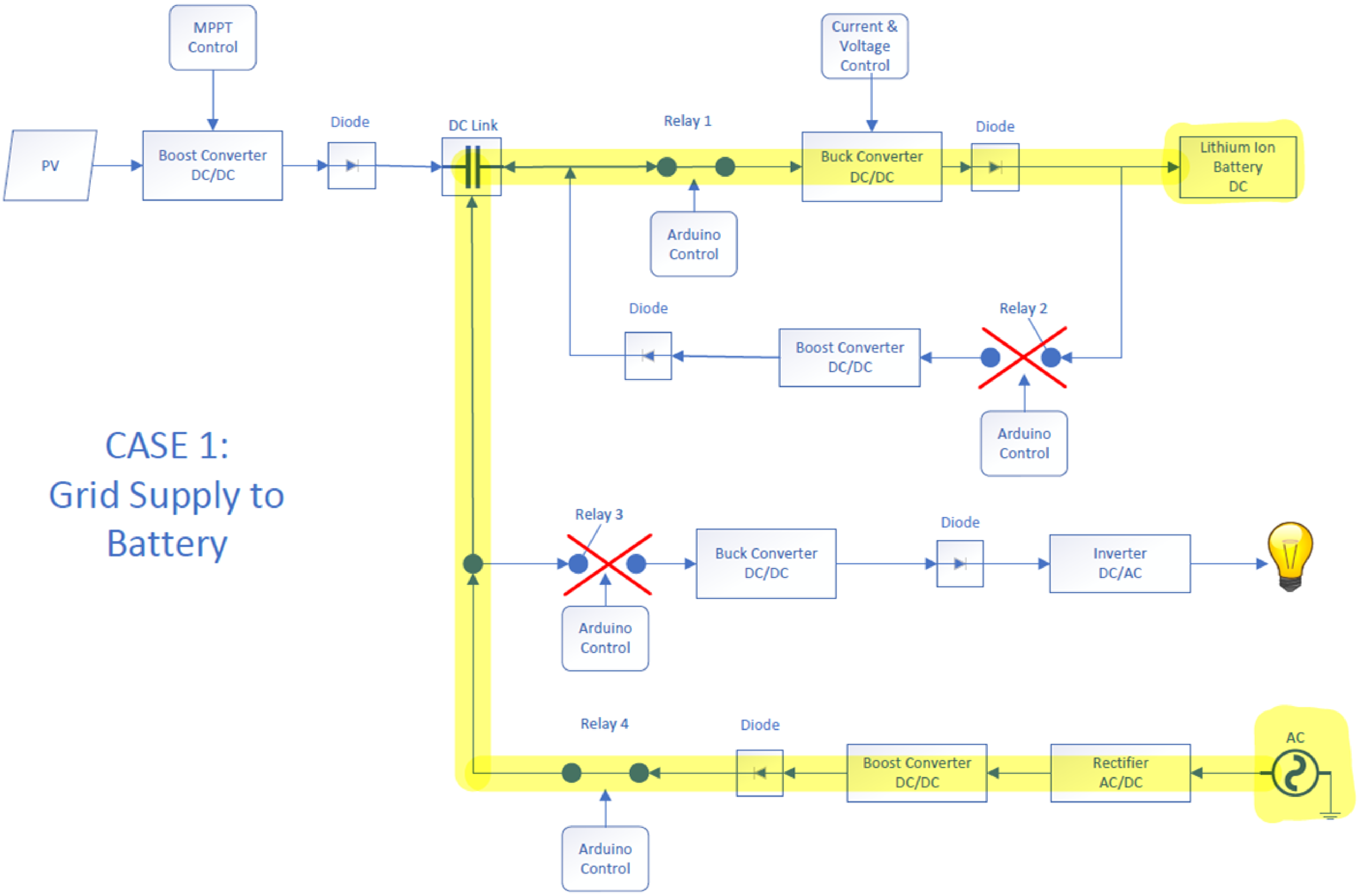
Requirement	Justification	Judges
The charging station should be available to use at all times	Grid integration ensures power is continuously available	✔
The system's bi-directionality should allow for grid optimization	Vehicles have the ability to be charged, or supply grid	✔
The system should be environmentally friendly	The system makes use of the PV system, minimizes losses	✔
The system should be enclosed, and offer protections for overcharging of batteries.	Monitors the SOC of EV battery	✔
The system must be able to monitor states of charge and switch over to the grid system when necessary	The system monitors state of charge.	✔
The system should minimize energy waste and maximize solar potential.	Produced energy waste is eliminated by returning it to the grid.	✔
The system should use DC charging	DC charging has been implemented.	✔

What are the risks and payoffs?

Risks	Payoffs
•Increases electricity demand on the grid •Random and unmanaged	•Allows for reduction of grid demand during peak periods by allowing customers to use their vehicle as an energy source
•EV battery degradation	•Protection against over-charging
•Cyber security risk •Communication with grid, vehicles	•Fast charging •DC charging
•Interoperability	•Fast charging •DC charging

DEMO

CASE 1: Grid Supply to Battery



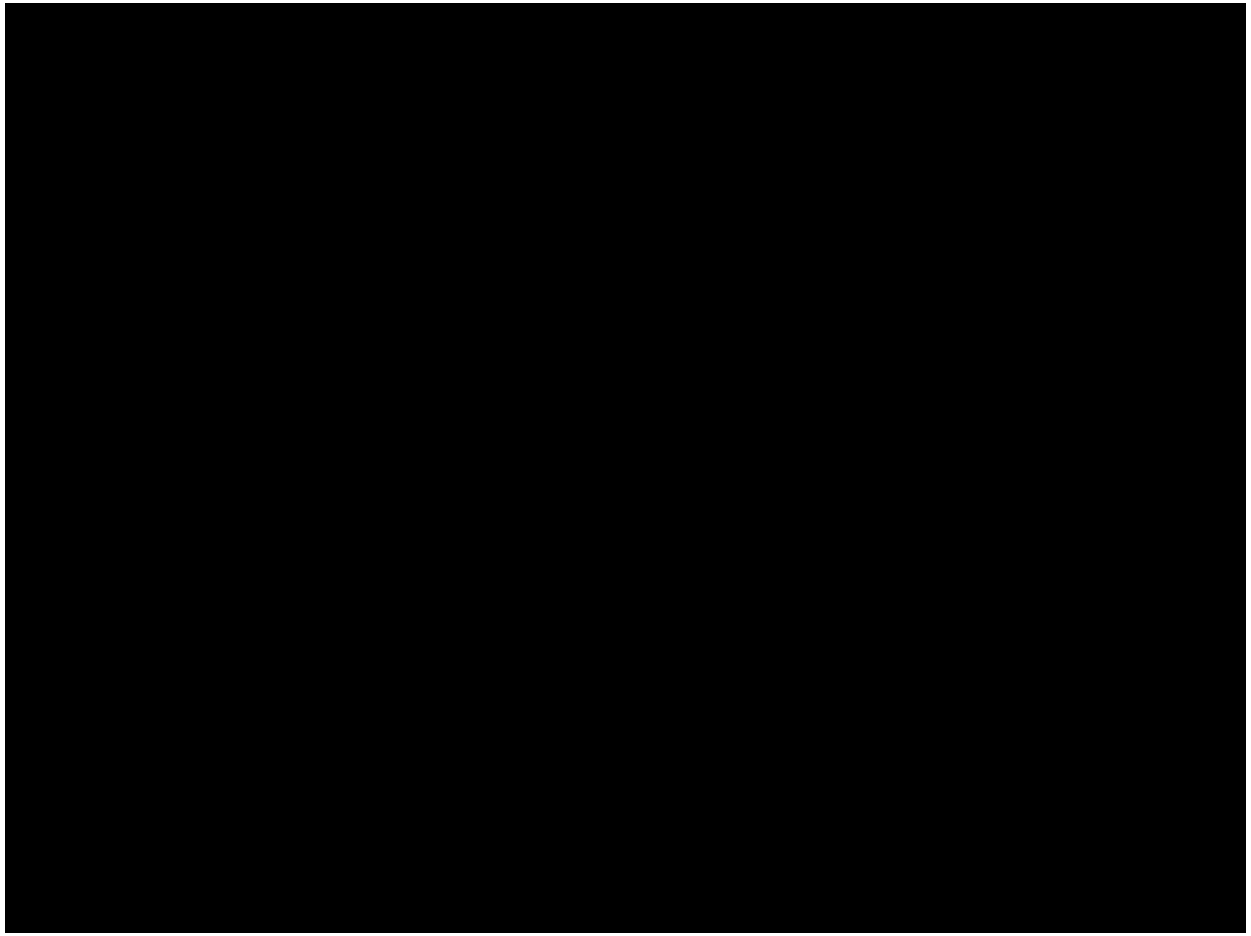
CASE 1: Grid Supply to Battery

Objective: Charge the EV battery

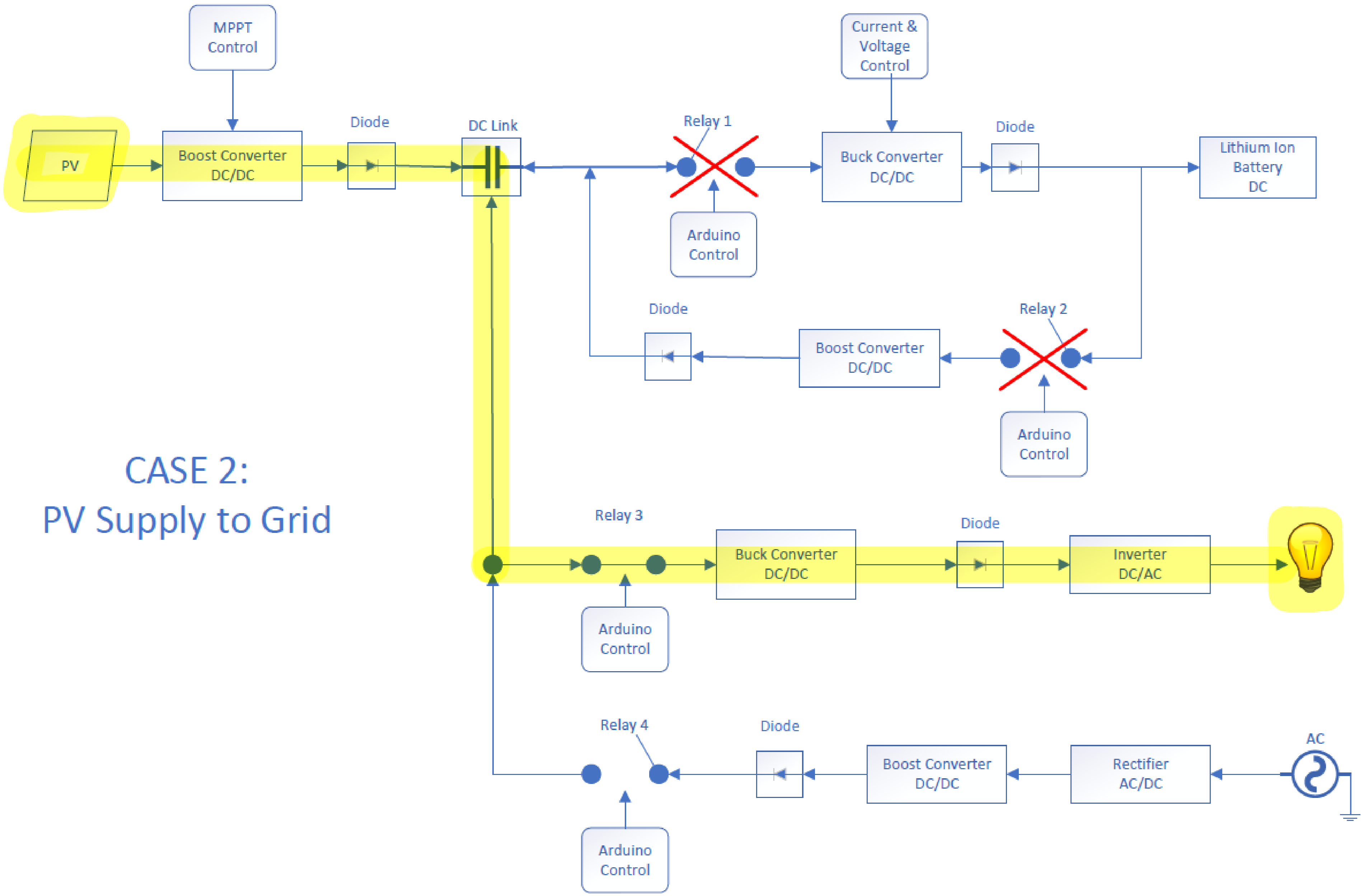
During times when the PV is not generating enough power or there is no available sunlight (i.e. over-night), our system is designed to take power from the grid when necessary in order to charge the EV battery as desired by the user. It will perform these actions through the following steps:

1. PV voltage sensor will read that there is not enough voltage from the source and the battery voltage sensor will read that the battery requires charging
2. Relays 1 & 4 will close while relays 2 & 3 will open
3. 120VAC Single phase is feed through the input of the rectifier and outputs 12VDC
4. The 12 VDC will flow through the boost converter and will step-up the voltage to 15 VDC to synchronize with the DC link voltage
5. Power then flows through relay 4 to the DC link and flows through relay 1
6. The 15VDC is then passed through the buck converter which steps-down the voltage to 12VDC
7. The battery is now being charged by the grid

CASE 1: Demo Video



CASE 2:
PV Supply to Grid



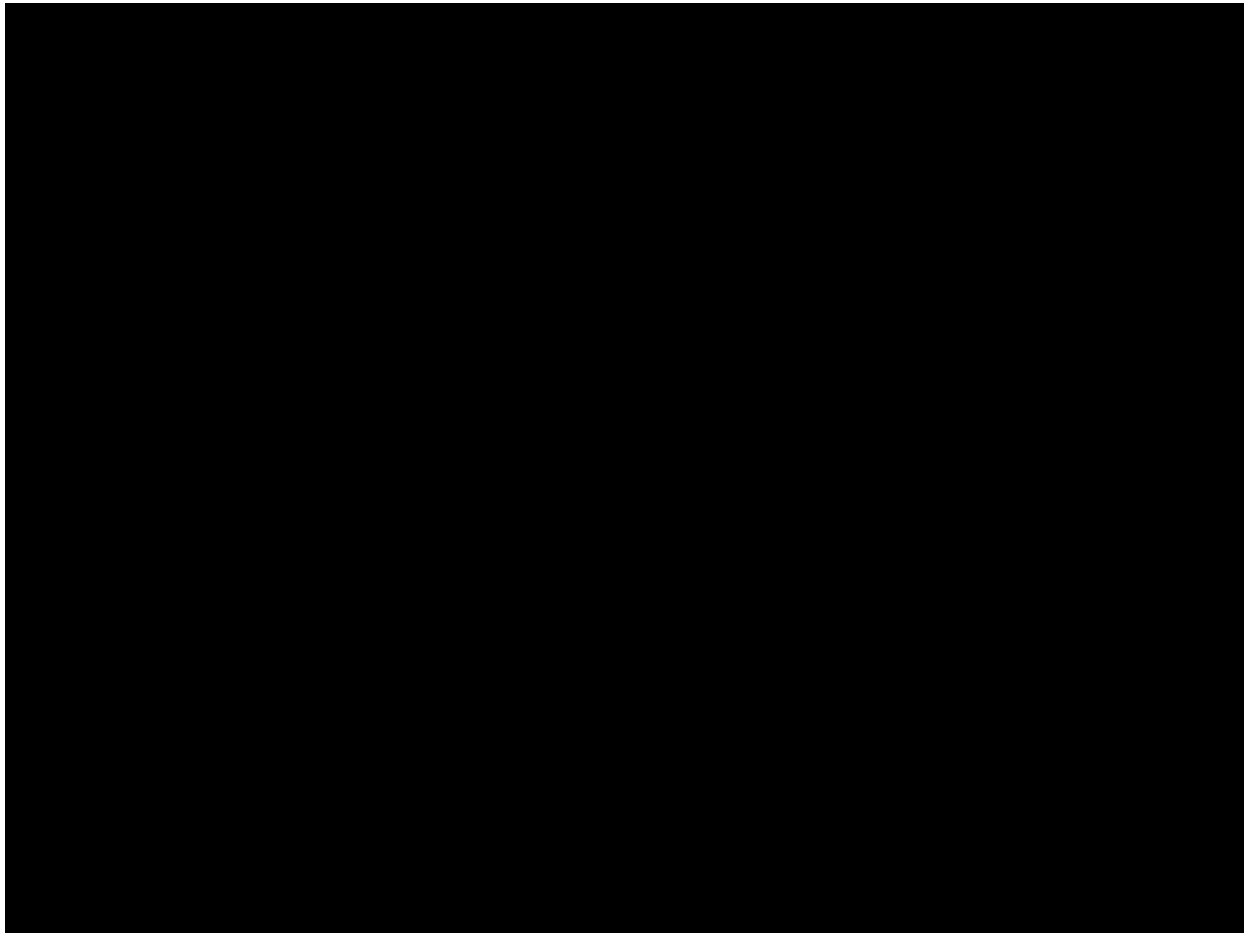
CASE 2: PV Supply to Grid

Objective: Supply the grid to reduce strain during peak hours

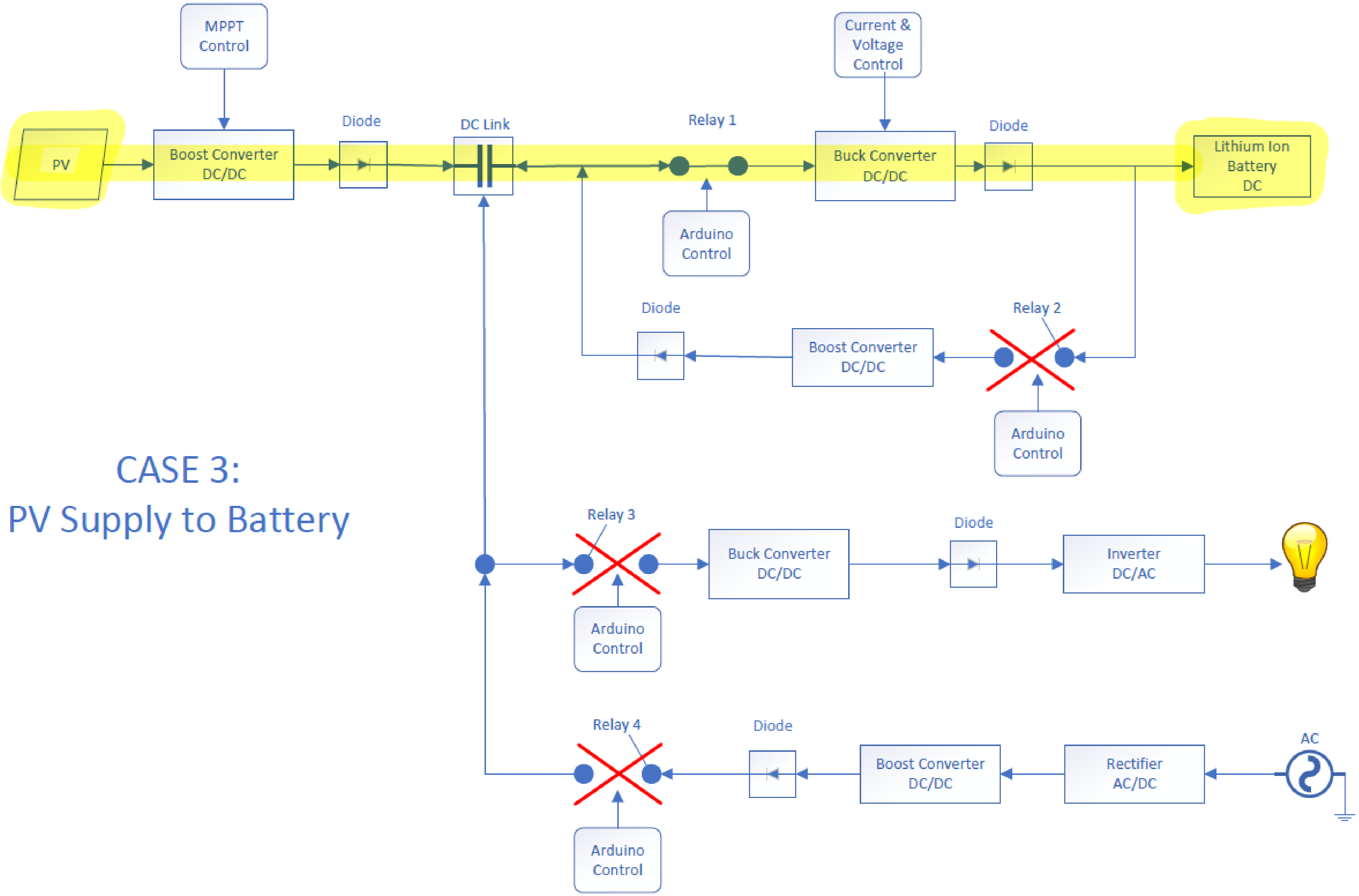
During times when the PV is generating enough power (i.e. an output of 12 VDC), but there is no EV at the station, our system is designed to supply the grid with power through our PV. It will perform these actions through the following steps:

1. PV voltage sensor will read that there is enough voltage from the source and the battery voltage sensor will read that there is no EV present
2. Relay 3 will close while Relays 1, 2, & 4 will open
3. The 12 VDC from the PV will flow through the boost converter which will step-up the voltage to 15 VDC to synchronize with the DC Link voltage
4. Power then flows from the DC Link and through Relay 3
5. The 15VDC is then passed through the buck converter which steps-down the voltage to 12 VDC
6. The output of the buck converter (i.e. 12 VDC) acts as an input to our grid inverter, which in turn supplies 120 VAC back to the grid

CASE 2: Demo Video



CASE 3:
PV Supply to Battery



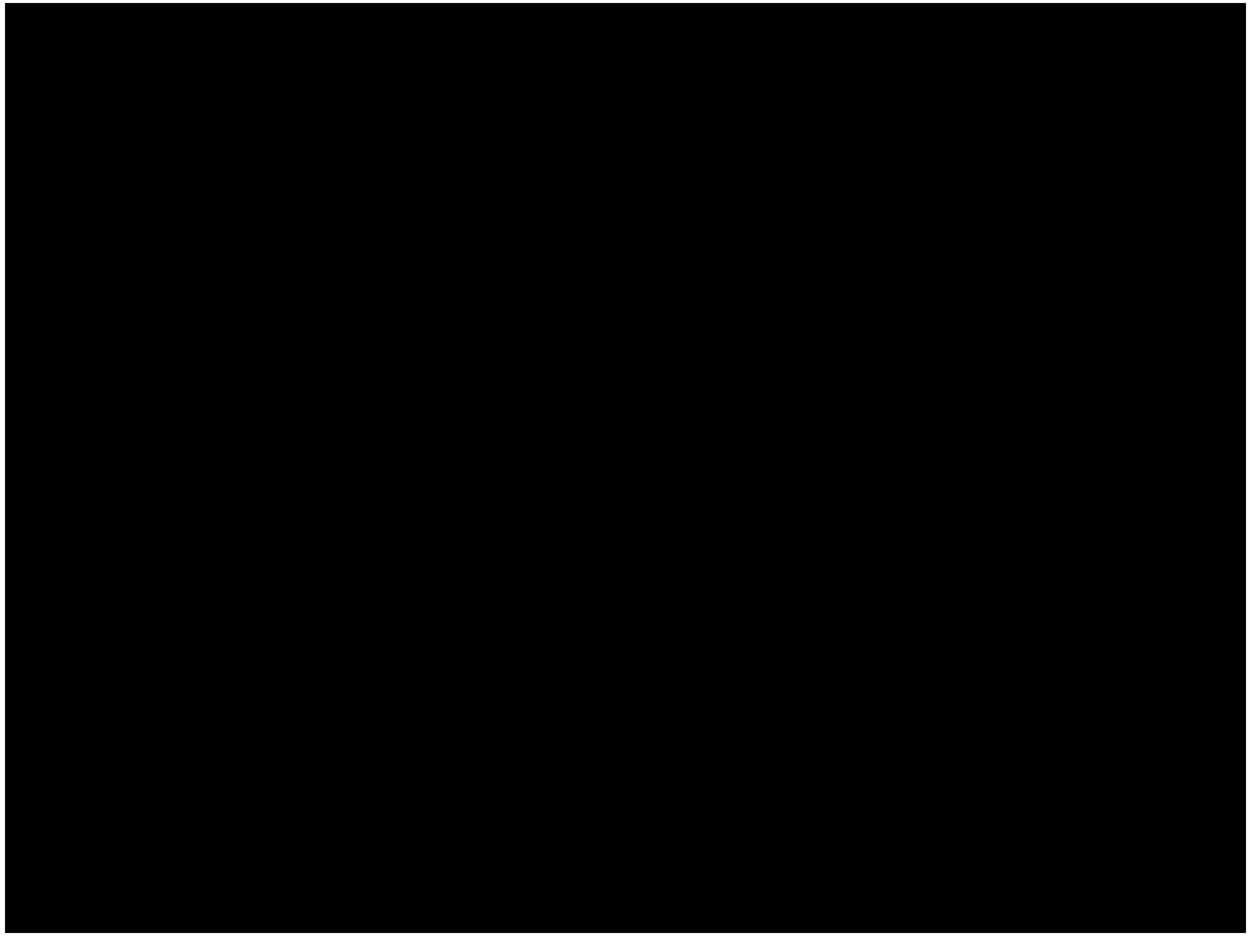
CASE 3: PV Supply to Battery

Objective: Charge the EV battery using power supplied from the PV supply.

During times when the PV is generating enough power (i.e. a steady output of 12 VDC), while an EV with less than a 100% SOC is present, the PV system charges the EV battery. This is accomplished through:

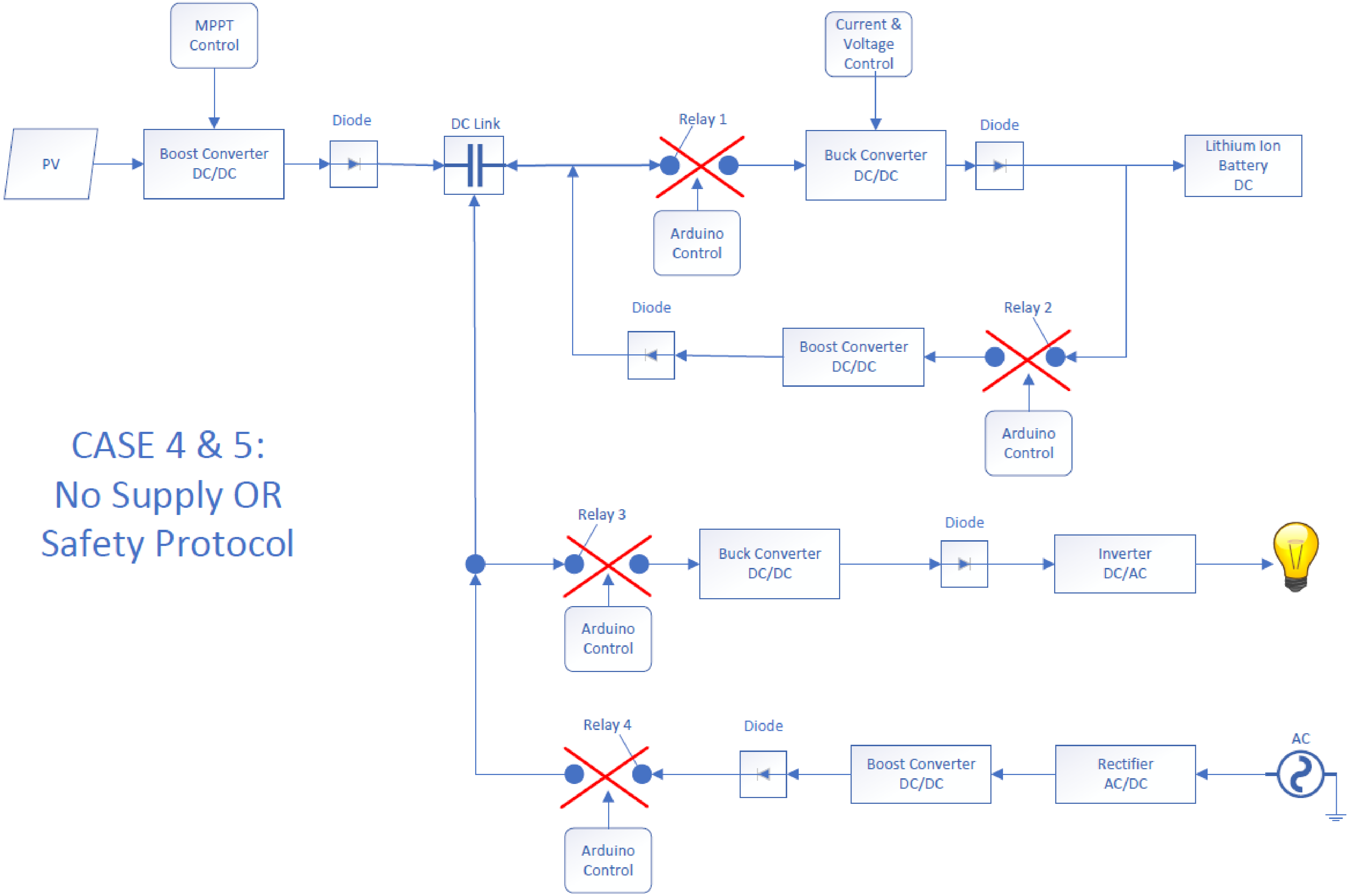
1. PV voltage sensor will read that there is sufficient voltage from the PV source and the battery voltage sensor will read that there is an EV present, and it's SOC < 100%
2. The contacts of Relay 1 will close while Relays 2, 3, & 4 will open
3. The 12 VDC from the PV will flow through the boost converter which will step-up the voltage to 15 VDC to synchronize with the DC Link voltage
4. Power then flows from the DC Link, through the contacts of Relay 1
5. The 15VDC is then passed through the buck converter which steps-down the voltage to 12 VDC
6. The output of the buck converter (i.e. 12 VDC) acts as an input to our EV battery.
7. The state of charge of the battery is monitored by the voltage sensor. When the SOC meets 100%, the supply to the EV is shut off.

CASE 3: Demo Video



Current and Voltage for Battery Charging

CASE 4 & 5: No Supply OR Safety Protocol



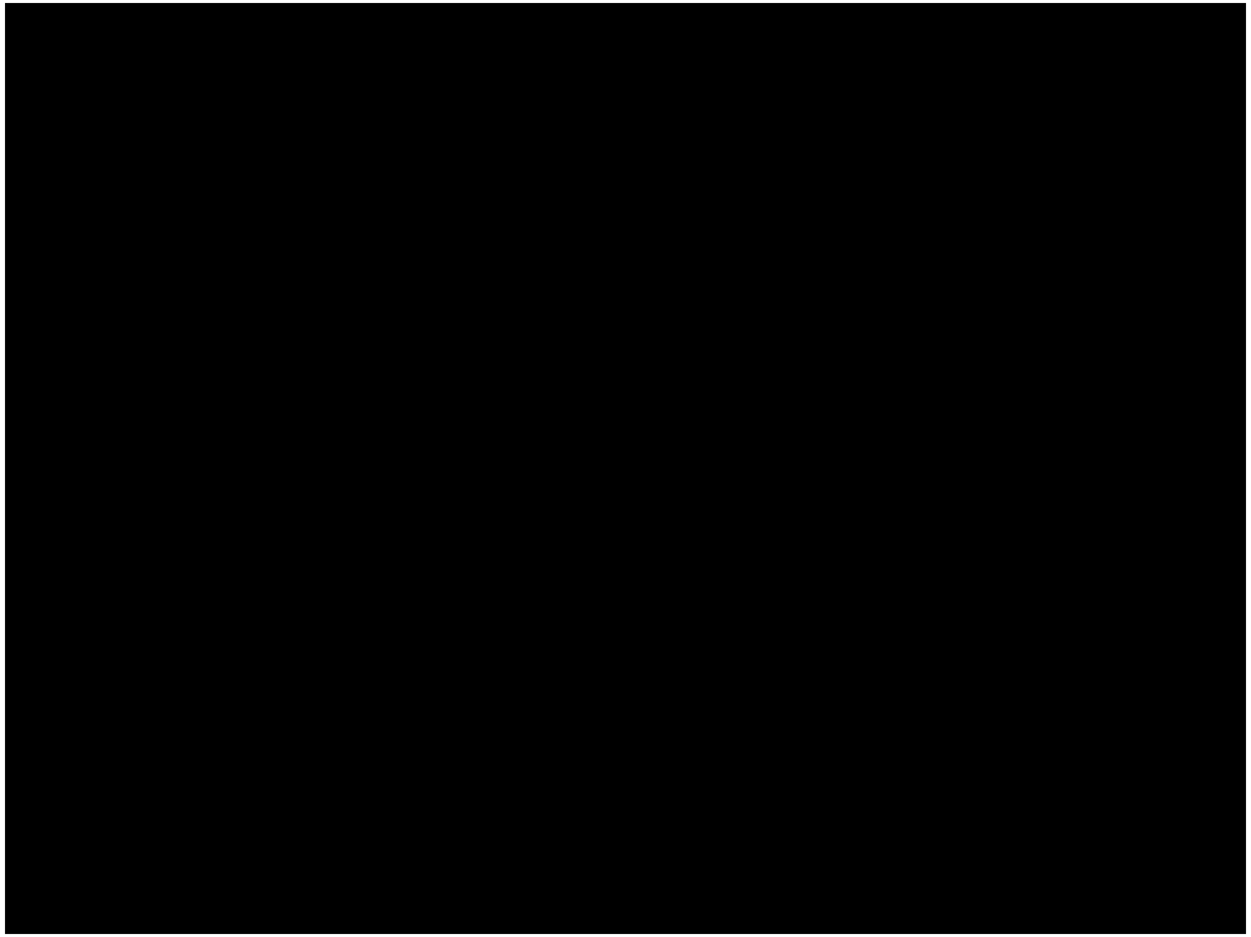
CASE 4: No supply OR CASE 5: Safety Protocol

Objective: Open ALL relays

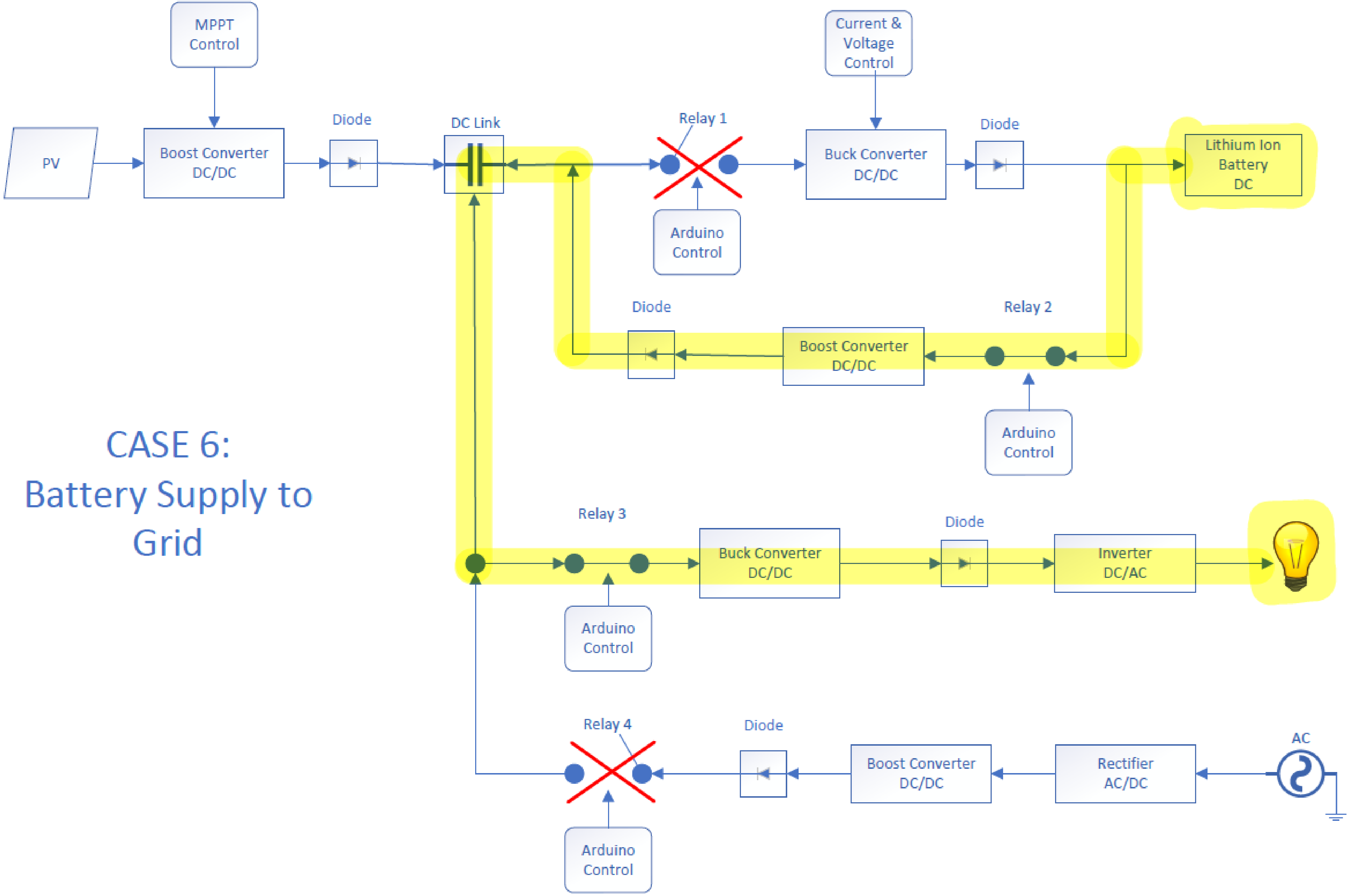
When there is no EV battery present and there is no power being generated by the PV, our system is designed to open all the relays to prevent any power flow. This case is to also act as a safety protocol in the event that none of the other cases are met, to prevent any power flow and limit the potential damage to the system. These actions are performed by the following steps:

1. Both the PV and the battery voltage sensors will either read no voltage or an abnormal voltage level
2. This will trigger all the relays to open
3. The breaks the power flow between all three subsystems (EV side, PV side, and Grid side)

CASES 4/5: Demo Video



CASE 6:
Battery Supply to Grid



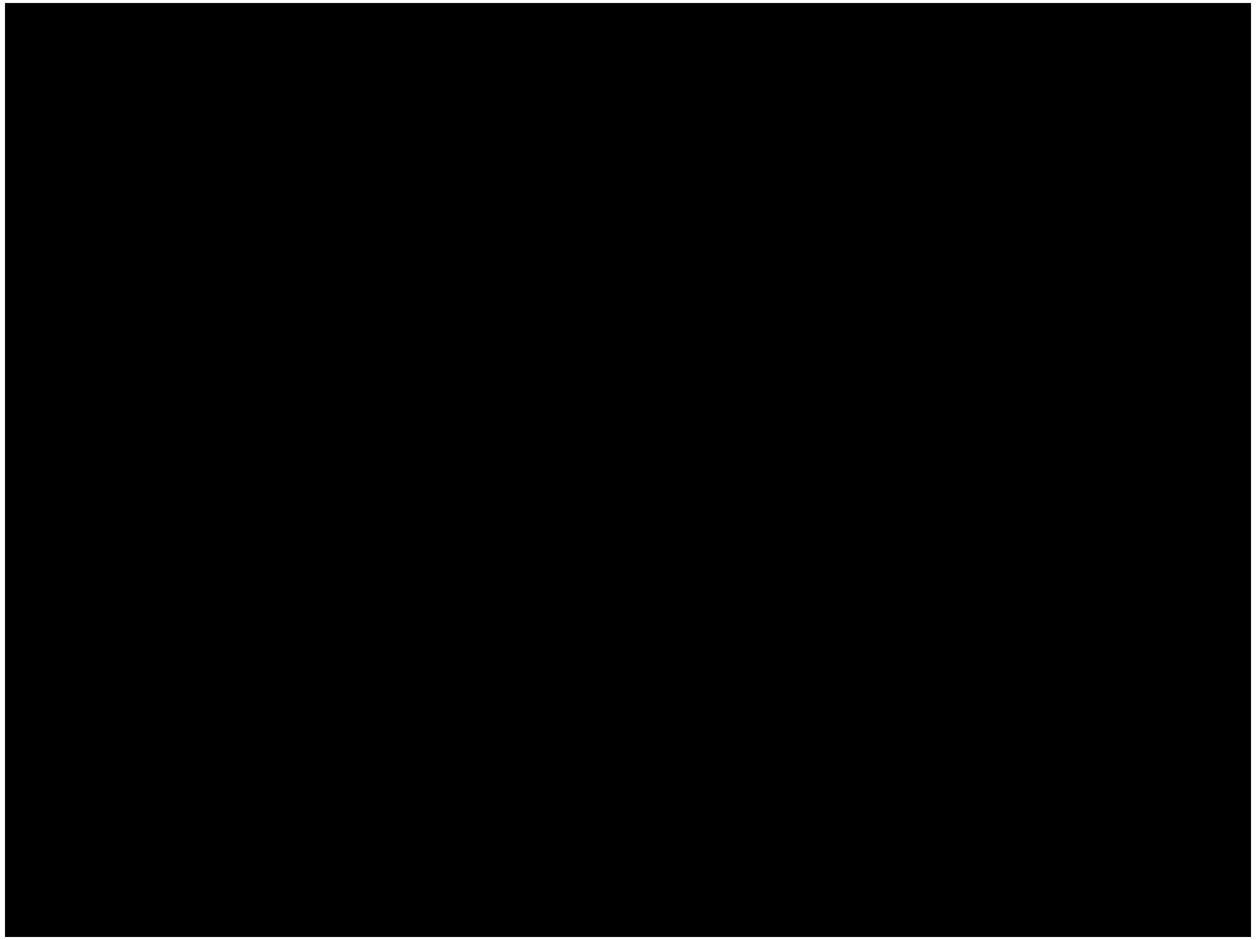
CASE 6: Battery Supply to Grid

Objective: Supply the grid from the EV battery to reduce strain during peak hours, incorporating demand response.

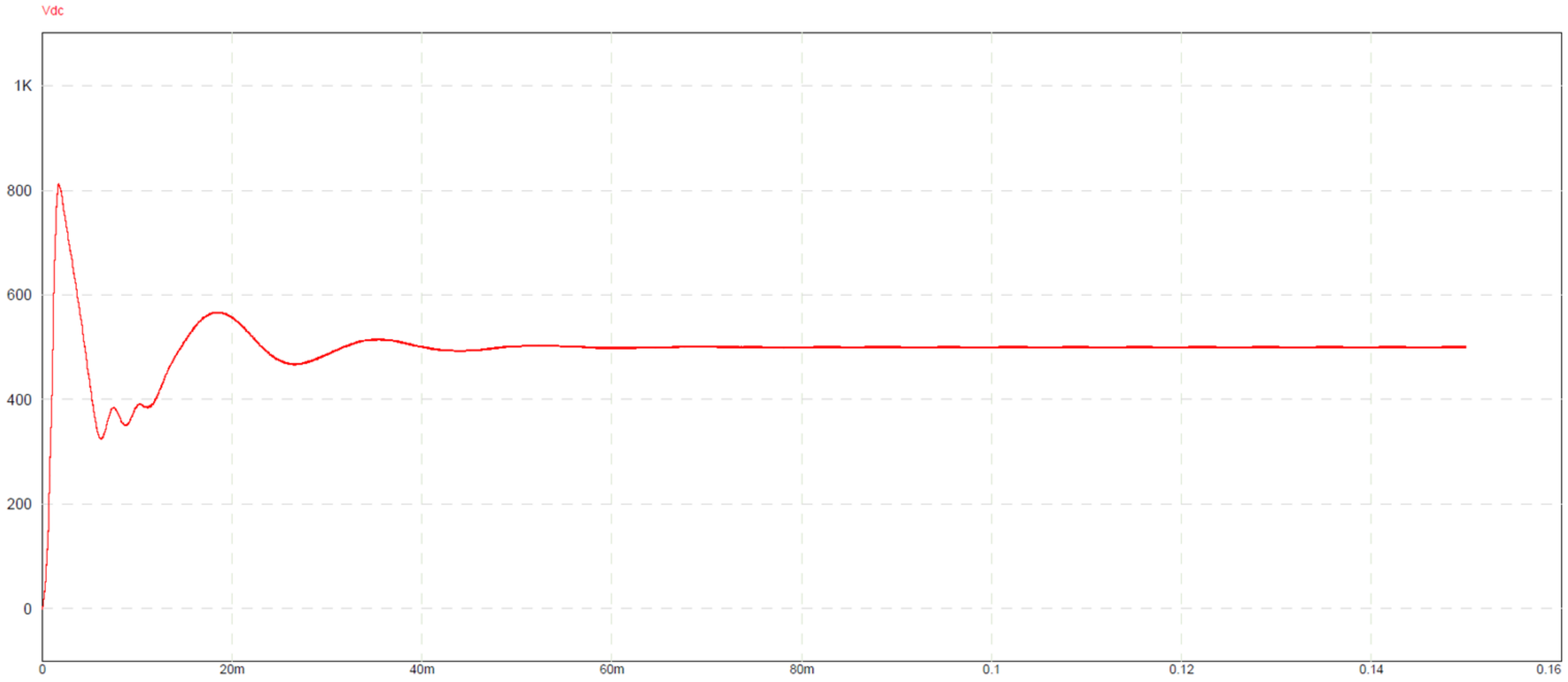
Upon the user connecting their vehicle to the charging station, the system measures the EV battery potential. The pushbutton simulates demand response signal from the utility, or the user manually selecting to supply the grid. Should the PV system be supplying power, it will also direct it towards the grid. The system will perform these actions through the following steps:

1. EV battery voltage sensor will read that there is enough potential from the battery.
    a. The voltage from the PV system is measured simultaneously. Should it be supplying 12VDC, this potential will be boosted to 15VDC and act as an input to the DC-Link
2. The contacts of relays 2 and 3 will close while relays 1 & 4 will open
3. The potential from the EV battery will flow through the boost converter which will step-up the voltage to 15 VDC to synchronize with the DC Link voltage
    a. If PV happens to be available simultaneously, steps 4,5 & 6 apply.
4. Power then flows from the DC Link and through Relay 3
5. The 15VDC is then passed through the buck converter which steps-down the voltage to 12 VDC
6. The output of the buck converter (i.e. 12 VDC) acts as an input to our grid inverter, which in turn supplies 120 VAC back to the grid

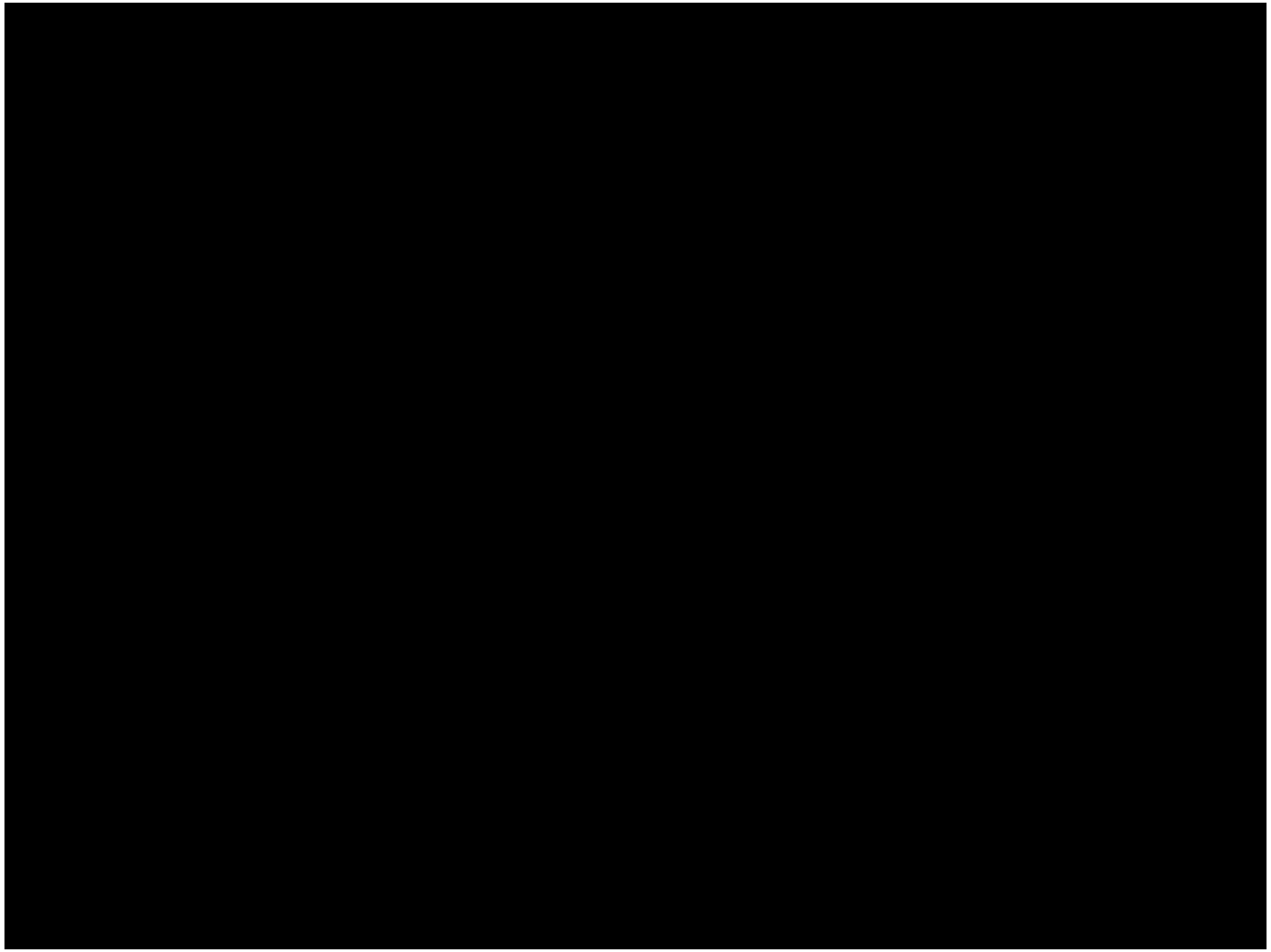
CASE 6: Demo Video



Voltage Across the DC Link



System-Level Overview:



Thank you.